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Life cycle assessment for co-firing semi-carbonized fuel manufactured using woody biomass with coal: A case study in the central area of Wakayama, Japan

Tomohiro Tabata[a,*], Hitoshi Torikai[b], Mineo Tsurumaki[c], Yutaka Genchi[d], Koji Ukegawa[b]

[a] Kobe University, 3-11 Tsurukabuto, Nada-ku, Kobe City 657-8501, Japan
[b] Industrial Technology Center of Wakayama Prefecture, 60 Ogura, Wakayama City, Wakayama 649-6261, Japan
[c] Wakayama National College of Technology, 77 Nojima, Nata-cho, Gobo City, Wakayama 644-0023, Japan
[d] National Institute of Advanced Industrial Science and Technology (AIST), 16-1 Onogawa, Tsukuba City, Ibaraki 305-8569, Japan

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ABSTRACT

Reducing the use of fossil fuel is one of the prime tasks for preventing climate change. The worst fossil fuel in this regard is coal, which is the largest CO_2-emitting fossil fuel in terms of weight. Although decreasing the use of coal is difficult because of its increasing demand in worldwide, there is still a possibility of effectively reducing greenhouse gas (GHG) emissions by substituting biomass, even for a subset of coal. One way to reduce the use of coal is to implement co-firing of biomass with coal at coal thermal power stations. In this study, the business impact of GHG reduction from semi-carbonized fuel produced by co-firing woody biomass with coal in thermal power plants is evaluated from the perspective of life cycles, using the life cycle assessment (LCA) methodology. The case study area is the central region of Wakayama prefecture, Japan. In this study, a new business is considered whose operations would co-fire the woody biomass with coal. A life cycle inventory (LCI) analysis and a life cycle impact assessment are conducted to evaluate the GHG emissions, taking into account processes such as cutting timber, manufacturing semi-carbonized fuel, and co-firing with coal. LCI data was collected and calculated on the basis of the feasibility study and literature survey. The spatial distribution of the woody biomass was ascertained using a geographic information system, and the location of several facilities and a road transportation network were determined. Results showed that an annual reduction in GHG emissions of approximately 46,700 tonnes in the case study area is possible if the business is executed. The environmental impact taking into account climate change, acidification and land use was also reduced. As the result, this business is in fact advantageous to reduce GHG emissions as well as the environmental impact.

Contents

* Corresponding author.
E-mail address: tabata@people.kobe-u.ac.jp (T. Tabata).

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1. Introduction

Diminishing the usage of fossil fuel is one of the prime tasks faced in the prevention of climate change. The worst fossil fuel in this regard is coal, which is the largest CO_2-emitting fossil fuel in terms of weight. Coal use has nevertheless been increasing worldwide because of its cheap price and the length of its reserve-production ratio. In 2008, 29.2% of the world's consumed primary energy was derived from coal [1], and 35.4% of the emitted CO_2 (approximately 9 billion tonnes of CO_2) in the entire world is derived from coal [2]. The complete abolition of coal usage in the short term is a difficult task. That said, there is still the possibility of effectively reducing CO_2 emissions by substituting biomass for even a subset of coal. Incidentally, in Japan, 25.4% of the primary energy consumption depends on coal [1]. Although the rate of coal consumption in Japan is lower than its mean value in the rest of the world (29.2%), the Japanese energy self-sufficiency ratio is approximately 4%. Japan therefore needs to reduce its dependence on imported fuel both to combat climate change and achieve energy security [3].

In Japan, coal is mainly utilized for electric generation and steel production. There have been several studies that address how to reduce the use of coal. One remarkable study in particular discusses the co-firing of biomass with coal at a coal thermal power station. In addition, there has been much R&D and many investigations regarding how to put such new schemes into operation [4,5]. The Japanese government has also focused attention on this area in terms of measures to prevent climate change and encourage sustainable forest management. These days, many Japanese local governments and power companies are committed to such study that is based on measures such as renewable portfolio standard (RPS) law, and an experimental project involving the co-firing of forest residue at several coal-burning power stations [6–8]. Despite the increasing attention it has received, biomass utilization remains an area that is weakly pursued because of its generally high business cost as compared with coal. In particular, woody biomass has weak cost competitiveness because additional processes such as cutting timber, chipping, drying and transportation are required [9]. To solve these problems, the manufacture of semi-carbonized fuel has been studied in terms of making it operational [10,11].

On the other hand, although DOE [5] says that it is possible to increase the mixing rate of biomass in the coal thermal power plant up to 20% of the coal weight ratio, Suzuki [12] asserts that the mixing rate can only go up to 3% to prevent a decrease in the performance of coal mills. Therefore, almost all of the biomass co-firing businesses in Japan use a standardized 3% of coal weight ratio, which seems to offer little advantage as a climate change measure. It is possible, however, to cut down approximately 270 million tonnes of the CO_2 emissions produced by coal if only 3% of the coal is replaced with biomass, on a weight basis [2]. This anticipated value corresponds to 21% of the greenhouse gas (GHG) emissions (approximately 1.3 billion tonnes of CO_2 equiv.) in Japan. In order to maximize this potential reduction, what is required is the development of an operationally feasible biomass co-firing technology that has high cost competitiveness.

In this study, an environmental impact including the effect of GHG reduction in a business setting, taking into account the co-firing of woody biomass with coal, is evaluated from the perspective of life cycles. Semi-carbonized fuel manufactured with woody biomass is the focus of this study, and methods to improve the effects of GHG reduction are investigated, using the life cycle assessment (LCA) methodology. The feasibility of this business is also investigated with consideration for the operational cost of reducing GHG emissions. Several studies have been conducted that evaluate the environmental load of the co-firing of woody biomass with coal, using LCA methodology [13–17]. Almost all of these studies, however, employ a virtual model and little actual value is given to life cycle inventory (LCI) data. It is therefore doubtful whether these studies reflect actual regional conditions and operations. This study offers a more realistic evaluation that focuses on a feasibility study in order to evaluate the effectiveness of producing semi-carbonized fuel from woody biomass.

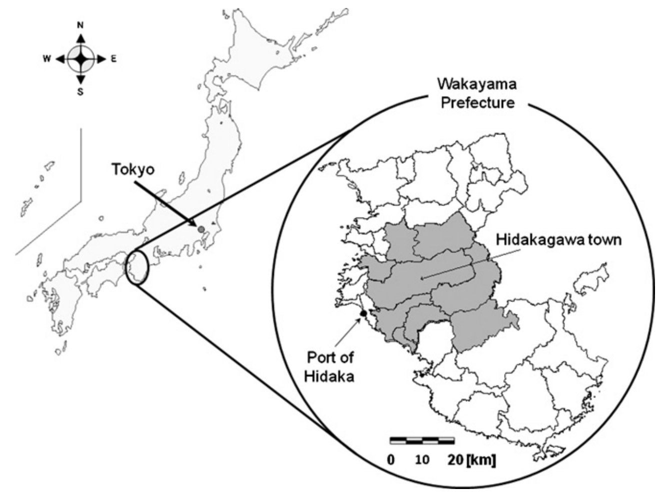


Fig. 1. Location of case study area.

2. Materials and methods

2.1. Case study area

The case study area is the central region of Wakayama prefecture, Japan, whose geographical location is indicated in Fig. 1. This region consists of six municipalities that occupy a land area of 1220 km^2. The population was approximately 68,000 in 2002, which corresponds to approximately 6.3% of the entire population of Wakayama prefecture. A large part of this region is mountainous, with the forest area occupying approximately 77% of the land area. The port of Hidaka is located on the west side of this region, and its function is to dock various vessels whose size ranges as high as large 30,000 tonne-class ships.

2.2. Semi-carbonized fuel

Larry [9] indicated that the problems associated with the co-firing of biomass with coal are the low heating value of the biomass because of its low energy density compared to that of coal, the difficulty of storage, and the difficulty of co-firing due to differences in particle size, corrosion, and the like. These problems cause poor handling in the co-firing process and increase the cost of operation. With semi-carbonized fuel, on the other hand, it is possible to compress the weight of the woody biomass while losing less of its volatilized carbon. This type of fuel resolves such problems as the difficulty of storage and corrosion. In addition, the heating value of semi-carbonized fuel is thought to be equivalent to that of coal, due to its high energy density. It is also expected to be easy to pulverize. Thus, semi-carbonized fuel is the focus of our attention as a technology to reduce operational costs.

To manufacture semi-carbonized fuel, first, chipped woody biomass is semi-carbonized at a low temperature of around 280–290 °C. It is then formed and shaped into briquettes. Semi-carbonized fuel has the following notable features:

- It is possible to increase its heating value to equal that of coal (26.6 MJ/kg).

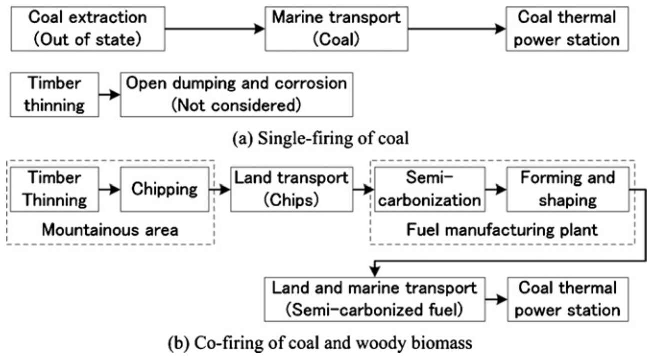


Fig. 2. System boundaries.

- Lower treatment cost is expected because of its high bulk specific gravity.
- Less additional load on the coal mill pulverizer is expected, as compared to woody biomass.
- Additional processes such as semi-carbonization and forming and shaping are needed.
- The fuel weight is less than that of woody biomass because little volatilized carbon is lost in the semi-carbonization process.

2.3. Evaluation method

In this study, a new business was hypothesized to operate the co-firing of woody biomass with coal in the case study area. LCI analysis and life cycle impact analysis are conducted to evaluate the environmental impact including the GHG emissions, taking into account processes such as cutting timber, the manufacture of semi-carbonized fuel, and co-firing it with coal. The environmental impact and the effect of reduced GHG emissions is also evaluated and compared for the co-firing of coal and woody biomass, and the single-firing of coal. The woody biomass employed in the study is composed of Japanese cedar (*Cryptomeria*) and Japanese cypress (*Chamaecyparis obtusa*). Approximately 28.3% of the forests in Japan are composed of these tree species, which were cultivated throughout Japan in a tree-planting program of the central government after 1945 [18]. Timber thinning, however, is relatively non-functional these days because of the slumping Japanese forestry industry. In addition, adverse events such as landslides, pollen allergy, and the production of immature trees with a low commodity price are severe problems in Japan. For these reasons, sustainable forest management for these types of timber has been emphasized [19].

Fig. 2 indicates the system boundaries. Two evaluation cases were supposed: one involves the single-firing of coal, the other involves the co-firing of coal and woody biomass. In the former case, the coal is extracted out of state and is transported to Japan by marine transport, after which the coal is fired. Timber thinning is taken into account in this case because standardization of the system boundary between the two cases is required for LCA. It is supposed, however, that thinned timber is not utilized, dumped and corroded. Then, although Keppler et al. [20] indicate that dumped timber causes the emission of methane into the air from corrosion, the generation mechanism of methane is not known in full detail, which is why methane emission from thinned timber was not considered in this study. In the latter case, first the forest is thinned and then the thinned timber is chipped in a mountainous area. Next, the chips are transported by dump trucks to the fuel manufacturing plant via a transfer station. The collected chips are semi-carbonized in the plant and then formed and shaped into fuel briquettes. After this, the semi-carbonized fuel is transported to the port of Hidaka (Fig. 1) by dump trucks and is transported to the coal thermal power station by bulker. At the coal thermal power station, coal and the semi-carbonized fuel are mixed and are pulverized in a coal pulverizer. After this, they are co-fired.

In order to calculate the LCI data, the system boundary was divided into five processes: (1) thinning and chipping, (2) land transport of chips, (3) fuel manufacture, (4) land and marine transport of semi-carbonized fuel, and (5) co-firing.

The environmental load employed in the study was GHG (CO_2, CH_4, and N_2O). NO_x, SO_x and residue as ash of semi-carbonized fuel were also employed as the environmental load to take into account the environmental impact excepting GHG. These GHG were evaluated by weighting in the CO_2 equivalent using the factor of global warming potential for a time horizon of 100 years, namely CO_2: 1, CH_4: 25, and N_2O: 298 [21].

2.4. Case study

The case study that this study is used was taken into account the transportation distance of the chips and semi-carbonized fuel and the location of the plant. The reasons to address the location of the fuel manufacturing plant are: (1) the transport distance varies by plant location, (2) the number of plants and the manufacturing scale of the plants varies by transport distance, and (3) the LCI data changes according to the manufacturing scale of the plant. Chips are usually of low bulk specific gravity, and their long distance transport has both economic and environmental disadvantages. For this reason, deciding the location of a plant and its scale of manufacturing are important factors.

Basing on above reasons, Fig. 3 presents a brief description of the three evaluation cases. Chips are transported from mountainous areas to the fuel manufacturing plant via a transfer station by 2-tonne and 12-tonne dump trucks in all cases. There are six transfer stations in the mountainous area, and one fuel manufacturing plant is placed in the mountainous area. In the next section, how the number of transfer stations and plants and the manufacturing scale of the plants were determined are discussed.

The feasibility study was conducted for a mountain forest of the case study area from November 2009 to March 2010. In this feasibility study, experimental factors such as timber thinning, chipping, land transport by dump trucks, and semi-carbonization were considered. Also, the fuel manufacturing plant was designed based on the burning characteristics of semi-carbonized fuel. In addition, the consumption of utilities such as light oil, gasoline, electricity, and water were estimated in each experiment. Literature data and catalogue data were also considered as being outside the scope of the feasibility study in such areas as marine transport. Table 1 presents the results of the feasibility study and a related survey.

2.5. LCI data

LCI data was collected for each process from the feasibility study and the literature survey. The functional unit employed was the GHG emission from the operations for each process for 1 MJ of fuel. Light oil consumed in land transport was calculated using minimum road transportation distances obtained from Google Maps API and MappleX Ver.9 (Shobunsha Publications, Inc.). Bunker A consumption in marine transport was calculated using the transportation distances between the port of Hidaka and the coal thermal power plant. Currently, 28 coal thermal power plants are operated by electric companies in Japan. Location of the power plant where semi-carbonized fuel is utilized did not specify, and the mean marine transport distance (1330 km) from the port of Hidaka to each power plant was considered. The reduction in GHG emissions due to the coal substituted at the coal thermal power plant was also considered.

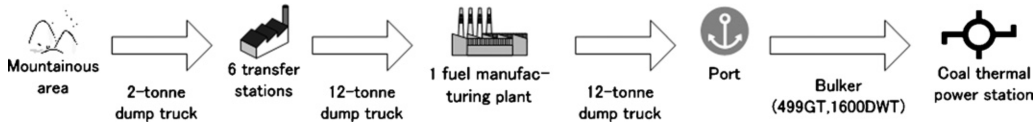


Fig. 3. Evaluation case.

After this, the unit GHG emissions using JEMAI-LCA Pro, which is an LCA software program for Japan, was calculated and summed them up as the GHG emissions. The GHG emissions were then calculated by multiplying the annual generation of thinned timber or chips or semi-carbonized fuel and the unit GHG emissions for each process. The GHG emissions not only in terms of transportation, fuel manufacture, and energy recovery, but also in terms of the construction of buildings such as transfer stations and fuel manufacturing plants, dump trucks, and the manufacture of utilities were considered. In a similar manner, NO_x and SO_x emissions were calculated. Amount of residue was supposed to correspond with 10% of semi-carbonized fuel basing on actual performance of the coal thermal power station.

2.6. Environmental impact assessment

For comprehensive evaluation of several environmental loads, the Distance to Target (DtT) method was applied. DtT is one of the methods for environmental impact assessment in LCA. DtT usually assigns a weighting coefficient to each environmental impact, and calculates an indicator value by integrating them [22]. The indicator value is calculated as follows.

$$I = \sum_i \left(\sum_s (Inv._s \times CF_{i,s}) \times \frac{1}{NV_i} \times \frac{NV_i}{T_i} \right) \quad (1)$$

where I: indicator value, $Inv._s$: amount of environmental load s, $CF_{i,s}$: characteristic coefficient of environmental impact i, NV_i: actual value of environmental impact i in Japan, and T_i: target value of environmental impact i in Japan or target set by an international organization.

The distance between the current and target values for an effect is calculated, and the greater the distance, the more serious the effect [22].

The following environmental impacts were taken into account: climate change due to GHG emissions, land use due to shortage of sanitary landfill, and acidification due to SO_x and NO_x emissions. These environmental impacts were chosen for the following reasons: climate change is a high priority issue in enhancing renewable energy; shortage of sanitary landfills is a local issue in countries such as Japan with a small land area, and this is of high priority in Japan; and it is important to check local pollution, such as acidification, caused by the renewable energy business. The following target values for 2030 relative to 2005 levels were set: reduction of GHG emissions by 63% to preventing global warming and climate change [23]; reduction of the final disposal volume by 80% to prolong the operational lives of sanitary landfills, because of the shortage of sanitary landfill, with reference to MSW management measures taken by several local municipalities in Japan; reduction of SO_x emissions by 21% and NO_x emissions by 17% to prevent acidification [24]. Characteristic coefficients of acidification gases were also evaluated by weighting SO_2 equivalents using a factor of deposition-oriented acidification potential – SO_x: 1 and NO_x: 0.72 [25].

2.7. Ascertaining geographic information

In order to determine the location of transfer stations and fuel manufacture plants, an investigation of the spatial distribution of the woody biomass, its vegetation, and the annual production of thinned timber was required. Therefore, a spatial distribution map of the woody biomass was created using a geographic information system (GIS). Vector data and mesh data regarding forest area, angularity, vegetation, road networks, national parks, and other pertinent factors were used for the map. In this study, areas where the maximum angularity exceeds 30° were excluded because of the high operational costs they would incur. National parks were also excluded because of the difficulties involved in conducting thinning as a business in them.

3. Results and discussions

3.1. Spatial distribution of thinned timber

Fig. 4 indicates the spatial distribution of Japanese cedar and Japanese cypress of the case study area. Each mesh (mesh area: 1 km^2) indicates the location of forest area. The shading of each mesh represents the size of the forest area. The total area of the woody biomass in the case study area was estimated using the spa-

Table 1
Results of feasibility study.

		Unit	Remarks
Annual generation of thinned timber	35	m^3/ha	Estimated data
Specific gravity of the woody biomass	0.91	tonne/m^3	Experimental data
Water content of the woody biomass	57.7	%	Experimental data, wet weight
Material loss	1.37	%	Evaporated water in chipping, experimental data
	43	%	Gas in semi-carbonizing (volatized carbon, etc.), experimental data, dry weight
Residual carbon in semi-carbonized fuel	74	%	Experimental data, compared to original woody biomass
Bulk specific density	0.34	–	Chips, experimental data
	0.60	–	Semi-carbonized fuel, estimated data
Working days	200	days/year	Tree thinning and chipping process and land transport (chips) one
	300	days/year	Fuel manufacturing process and land and marine transport (fuel)
	365	days/year	Co-firing process
Fuel consumption	10.5	km/L	2-tonne dump truck, experimental data, light oil
	5.4	km/L	12-tonne dump truck, catalogue data, light oil
	0.10	km/L	499GT type various vessels, DWT: 1 600, hold capacity: 2 490 m^3, Bunker A

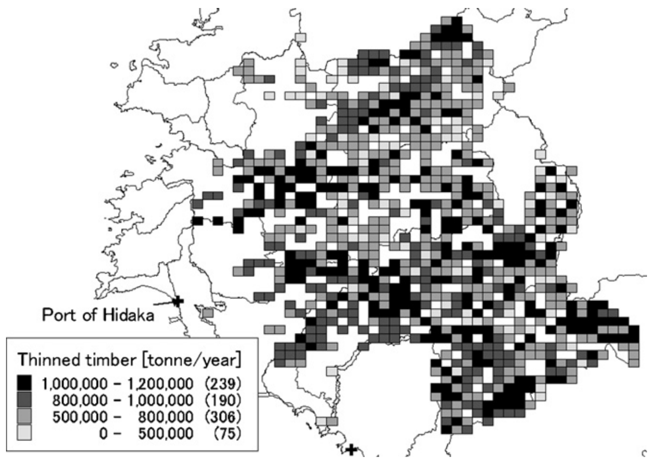


Fig. 4. Spatial distribution of thinned timber.

tial distribution map. The result was a total area of woody biomass that was approximately 88,900 ha, and a total area without an excluded zone that was approximately 65,600 ha.

Next, the annual generation of thinned timber in the case study area was estimated based on Fig. 4. The estimated data for the annual generation of thinned timber is 35 m^3 per 1 ha, and the specific gravity of the woody biomass is 0.91 tonne per 1 m^3, from Table 1. Thus, the annual generation of thinned timber in the case study was approximately 2,089,000 tonnes in wet weight. This total, however, represents the potential for woody biomass generation, and sustainable management would be difficult if all of the timber available for thinning were thinned in one year. Therefore, the forest area available for thinning is supposed to subdivide into twenty sections, with thinning conducted at a rate of one section per year. Based on this assumption, the annual generation of thinned timber in each section was approximately 104,460 tonnes.

Next, the location of transfer stations and plants was investigated according to the spatial distribution of the woody biomass. It was supposed that six transfer stations would be located at intersections such that everywhere in the entire forest area was within 10 km of a station. Fig. 5 indicates the locations of the transfer stations. Chipped timber in each forest area within a transportation zone is transported to the transfer station in that zone. If a forest area is overlapped by several zones, the transportation zone that is the minimum transport distance from the forest area is given priority.

The material flow of the woody biomass was estimated as shown in Table 2, taking into account the annual generation of woody biomass. The annual manufacture of semi-carbonized fuel is approximately 25,830 tonnes. If the daily consumption of coal were 8000 tonnes at a 1 GW-class coal thermal power station, an approximately 0.9% reduction of coal would become possible.

According to the above results for material flow, it was supposed that one fuel manufacturing plant with a capacity of 400 tonnes per day would be built. The location of each plant is indicated in Fig. 5.

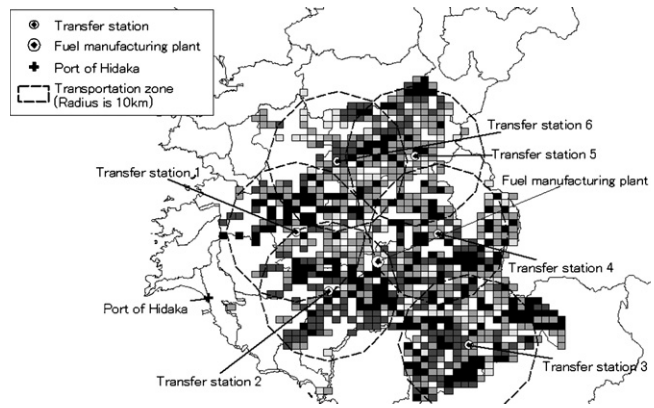


Fig. 5. Location of transfer stations and fuel manufacturing plants.

Table 2
Material flow of woody biomass.

		Unit	Remarks
Generation of thinned timber	104,460	tonne/year	
Production of chips	103,040	tonne/year	
Water loss in chipping	1420	tonne/year	By evaporation
Manufacture of semi-carbonized fuel	25,830	tonne/year	
Water loss in semi-carbonization	58,040	tonne/year	
Gas loss in semi-carbonization	19,170	tonne/year	
Lower heating value	26,600	MJ/tonne	Equivalent to coal
Amount of reduction of coal	25,830	tonne/year	

This location was determined by taking into account the location of the transfer stations or forest areas.

3.2. Results for environmental impact

Table 3 indicates the annual GHG, NO_x and SO_x emissions and residue. The net GHG emission is minus because of the large reduction in GHG due to the co-firing process. In the results, it is possible to reduce the GHG emission by approximately 46,700 tonnes annually. As a point of reference, the annual GHG emission in Wakayama prefecture was 16,372,000 tonnes in FY2003 [26]. This result implies that the effect of substitution is equivalent to approximately 0.3% of the GHG emission in this prefecture.

The process that produces the largest GHG emission is that of fuel manufacturing, which accounts for approximately 70% of the GHG emissions, excluding those from co-firing. The second largest GHG-emitting process is that of thinning and chipping, which accounts for approximately 15% of the GHG emissions, excluding those from co-firing. Focusing our attention upon the transport process, this process is the least GHG emission in all processes. This result suggests that the fuel manufacturing operations should take place in a mountainous region to increase the transport efficiency. Nevertheless, the GHG emissions in the transport process are less than in the other processes, and an increase in transport efficiency offers advantages from an economic viewpoint.

Table 3
Results of annual environmental load emissions.

	GHG [tonne-CO_2 equiv.]	NO_x [tonne-NO_x]	SO_x [tonne-SO_x]	Residue [tonne-residue]
Thinning and chipping process	3363	1.86	1.22	
Land transport (chip) process	96	0.12	0.14	
Fuel manufacture process	9126	4.44	6.89	
Land and marine transport (fuel) process	1340	0.66	0.93	
Co-firing process	−60,691	−1.26	−0.50	
Total	−46,767	6	9	2324

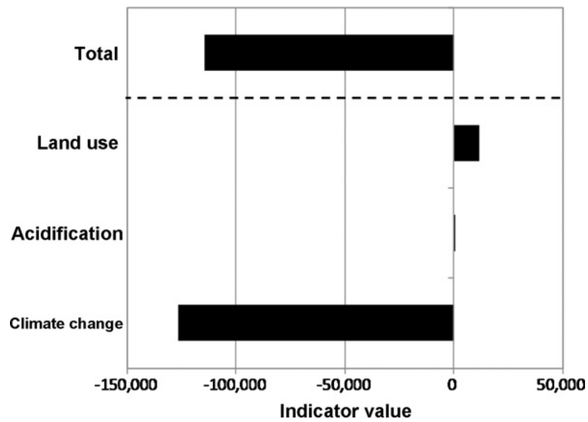


Fig. 6. Result of life cycle impact assessment.

The net NO_x and SO_x emissions are plus because the emissions in the fuel manufacturing process are higher than the reduction in the co-firing process.

Fig. 6 shows result of the life cycle impact assessment, taking into account the transition of target values. In the results, the net indicator value is minus because of large reduction in climate change. On the contrary, acidification and land use are a little bit contribution. This result implies that the co-firing of the semi-carbonized fuel has better effect from the viewpoint of the environmental impact.

3.3. Sensitivity analysis

The results above imply that the fuel manufacturing process is the main source of GHG emissions. As mentioned above, semi-carbonization is a developing technology. Therefore, the energy usage in semi-carbonization could increase beyond the results in this study, depending on the application conditions. For this reason, a sensitivity analysis was conducted to confirm to what degree GHG emissions would vary due to additional energy use in the fuel manufacturing process.

First, what proportion of the heating value of the semi-carbonized fuel is consumed in its manufacture was calculated. The lower heating value of the fuel was taken to be equivalent to that of coal (26,600 MJ/tonnes). The energy usage for the manufacture of 1 tonne of the fuel is 5000 MJ. This implies that approximately 18% of the heating value of the fuel is consumed in its manufacture. Next, how much the GHG emission would vary if the energy used in manufacturing the fuel were varied was investigated. Fig. 7 indicates the result, which is that the net GHG emission retains a minus value if the energy usage for manufacturing 1 tonne of fuel exceeds 36,000 MJ. As the result, the effect of GHG emission reduction is maintained despite the excess energy usage, such as the heating value of the semi-carbonized fuel, as long as approximately 35% of additional energy is required.

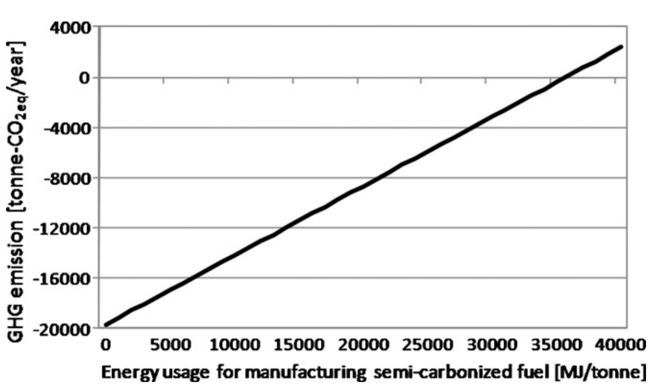


Fig. 7. GHG reduction effect, taking into account energy usage for the manufacture of semi-carbonized fuel.

4. Conclusions

In this study, the environmental impact including the GHG reduction effect of a business that takes into account the co-firing woody biomass with coal was evaluated from the perspective of life cycles. Then, the life cycle of GHG emissions from the timber thinning process to that of co-firing was evaluated. The result shows that it is possible to reduce the annual GHG emissions in the case study area by approximately 46,700 tonnes. The result also shows that it has better effect from the viewpoint of environmental impact. The proposed business is in fact advantageous as a net reducer of GHG emissions.

Future areas of investigation include an evaluation of how to implement a woody biomass manufacturing and co-firing system in a wider region. Because the mixing rate of semi-carbonized fuel with coal could exceed 3% in terms of the upward limit of its particle size [10], it is important to investigate how much semi-carbonized fuel it is possible to mix with coal, and how much GHG reduction can then be expected. An evaluation would also need to be conducted for conditions such as tree cultivation, land conditions, road distance, and other factors that are variable. The development of LCI data would be required in order to deal with these varying evaluation conditions.

Acknowledgements

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